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Research Paper

Experimental study and performance prediction of the PCM-antifreeze solar thermal system under cold weather conditions

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HIGHLIGHTS

- A novel PCM-antifreeze solar thermal system is proposed and designed.
- An experimental setup is built and mathematical model is presented.
- The antifreeze performance of the system is analyzed.
- Parametric study and seasonal analysis are conducted.

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ABSTRACT

This paper proposes a novel PCM-antifreeze solar thermal system which incorporates a specific amount of phase change material (PCM) into the conventional flat-plate solar thermal system (FPSCs) to prevent the system from freezing damage under cold weather conditions. Previous studies about the freeze prevention of the FPSCs mainly focus on the development of the antifreeze auxiliary system (electric or manual) which will reduce the system reliability. This work presents a study for a low cost and effective PCM-antifreeze solar thermal system. The experimental setup is built and the mathematical model is presented for the system. The daytime working and night antifreeze performance of the system are evaluated. Results show that the seasonal average freezing risk index of the PCM system is 8% while the value for conventional system is 66%.

1. Introduction

Flat-plate solar collector thermal system (FPSCs) is the most common solar thermal system for solar water-heating which has been widely used in residential and industrial low temperature application devices due to the high thermal efficiency and reliable performance [1]. Conventional FPSCs usually consists of the collector, circulation pipes, circulation pump and water tank. The absorber plate and flow channels (pipes) are the key components of the collector. The water in the flow channels extract the solar energy through the absorber and transfer the energy into the water tank during the daytime working. However, after the system stops working, the temperature drop of the water inside the collector is significant especially under cold weather conditions. Compared with the evacuated tube solar collector, the flat-plate solar collector has a relatively lower thermal insulation performance. The heat convection in the airgap (poor sealing) between the glass cover and the direct radiation of the collector to the sky dome lead to the high heat dissipation rate of the collector. J. Salasovich's study [2] shows that, the FPSCs may get freeze even when the ambient temperature is higher than 0 °C due to the fact that the sky equivalent temperature is much lower than the ambient air temperature. E.Zambolin [3] experimentally compared various working performance of the FPSC and the evacuated tube collector. The results show that although the FPSCs has the advantages of high thermal efficiency and high pressure bearing capacity, the FPSCs will suffer from heavy freezing damage during the winter season. When the freezing happens in the FPSCs, the strain caused by the volumetric expansion of water can burst the flow channels and cause the breakage of the collector if not using the antifreeze fluid.

Several researches have been reported on the winter working characteristics and freeze protection of the solar collector thermal system especially for the FPSCs. Most of the previous studies focus on the antifreeze methods of adopting antifreeze liquid recirculation, using automatic drainage device for emptying (drain back after the circulation pump stop working) and using the heat pipe to replace the

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Nomenclature

Symbols

A	area [m^2]
C	specific heat [J/(kg•K)]
du	antifreeze duration [h]
D	outside diameter [m]
E	current iteration results [K&J/kg]
E^*	previous iteration results [K&J/kg]
FI	freezing risk index
h	heat transfer coefficient [W/(K•m^2)]
H	enthalpy [J/kg]
H_s^*	enthalpy of solid PCM at the melting point [J/kg]
H_l^*	enthalpy of liquid PCM at the melting point [J/kg]
I	solar radiation [W/m^2]
l	length [m]
m	mass per unit area [kg/m^2]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number
R	daily total solar radiation [J/m^2]
Ra	Rayleigh number
r	radial coordinate [m]
T	temperature [K]
T_m	phase change temperature [K]
t	time [s]
U	conduction heat transfer coefficient per unit length [W/(K•m)]
x	horizontal coordinate [m]
y	axial coordinate [m]
z	vertical coordinate [m]

Subscript

a	airgap (between absorber and glass cover)
b	bottom
bc	backboard
cv	convective
ct	manifold
e	external environment
f	fluid
fi	final state
g	glass cover
in	initial state
ins	insulation layer
iso	insolation area
jo	absorber-pipe joint
l	liquid
p	absorber plate
r	radiative
s	solid
t	pipe
u	upper
wa	water

Greek symbols

α	absorptivity [dimensionless]
δ	thickness [m]
ε	emissivity [dimensionless]
λ	thermal conductivity [W/(K•m)]
γ	latent heat [J/kg]
η	thermal efficiency
ρ	density [kg/m^3]
σ	Stefan-Boltzman constant [5.6697×10^{-8} W/(K^4•m^2)]
	collector tilt angle [rad]

conventional water flow channels [4–7]. S.Rittidech [8] designed and built an experimental prototype of a CEOHP (closed-end oscillating heat pipe) solar collector to investigate its performance. Their finding reveals that the CEOHP system offers the benefits of the absence of freezing during winter months when the ambient temperature is lower than −4°C. Although the freezing point of the working fluid in the heat pipe is much lower than 0 °C (*ex*: acetone, −94.9 °C), the heat conduction through the heat pipe to the manifold may lead to the water freezing in the manifold. In the study by E.Shojaeizadeh [9], the effect of using the propylene glycol–water as absorbing medium fluid in a flat-plate solar water heater is investigated experimentally. The results show that the system maximum freeze prevention temperature is −84 F (−64 °C). However, the secondary circulation of the working fluid (antifreeze fluid) increases the heat resistance from the absorber to the water tank which low down the thermal efficiency of the system. In addition to studies and patents about various antifreeze approaches, there are several studies about the antifreeze performance of conventional FPSCs. In the study by F Zhou [10], the cooling and freezing process of the conventional FPSC are investigated with a prototype FPSC setup. Their results show that it takes 1–2 h from the system stopping to system freezing under −5°C ambient temperature. The antifreeze performance of FPSC can improve a lot through optimizing the design (pipe space, pipe diameter, etc.). However, the improvement of the antifreeze behavior of the FPSCs is limited through the structure or materials optimization especially for the system installed in severe cold areas. In the present work, a novel PCM-antifreeze solar thermal system is proposed, which incorporates a specific amount of phase change material (PCM) into the conventional FPSCs to prevent the

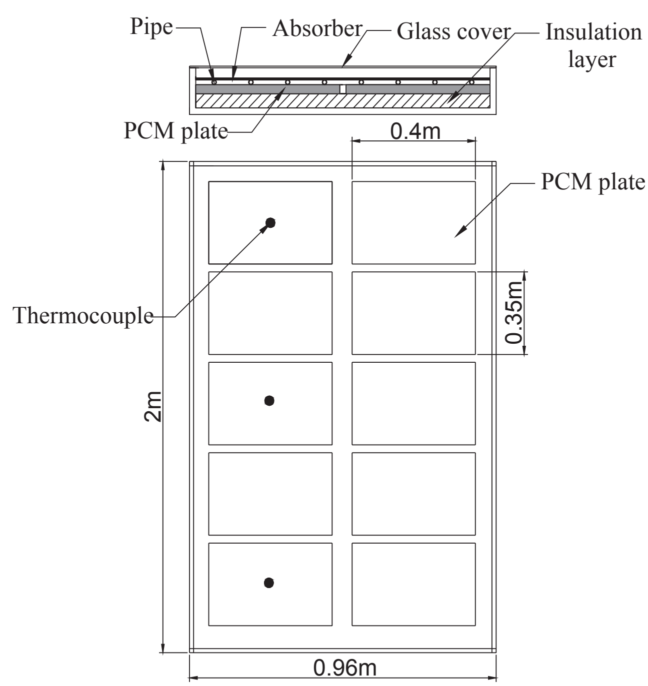

Fig. 1. The design of the PCM-antifreeze solar collector.